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Constellation Orbit Design Criteria for a Dual Use EO system

(13)

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Introduction:

In this paper the work concerning the definition of specific criteria for the orbit design of a Dual Use Earth Observation satellite constellation is presented.

These criteria have been derived by considering a wide range of civilian applications (e.g. risks management, agriculture/forestry, marine/coastal, geology) and military applications (surveillance, intelligence, crisis management, mission planning). In fact, for each of the application areas and the relevant EO products, a list of specific observation constraints have been identified and discussed in order to address optimal solutions allowing the timely generation of products characterised by a high level of quality and information content.

On the other hand, implementation/operational constraints and system complexity evaluation have been also considered in the constellation design process.

From the identification of candidate specialised orbits (elliptical orbits, inclined orbits and circular orbits) a specific system level trade-off has been performed in order to identify the best satellite constellation configuration in terms of orbit type, orbit planes, satellite phasing which allows to maximise the main performances (coverage and revisit times) for a given number of operational satellites.

This trade-off takes in to account the payload type (i.e. optical or SAR), the payload characteristics and constraints (e.g. field of view, resolution, dimension, power demand, illumination condition, interferometric capabilities and system complexity), the payload operational modes and spacecraft limitations due to drag effects and propulsion.

A detailed parametric analysis will be provided by showing the relationships between the system performances and the main design drivers.

Mission requirements for Dual-Use systems:

A dual use EO system shall be configured in order to satisfy specific needs of civil (institutional, commercial) and military users.

Given the wide range of applications to be covered, a dual use scenario calls for a mission which implements in an harmonic fashion several different operational modes characterised by a different priority with a suite of multi-mode/flexible sensors with an high thematic content, allowing to meet the military and the civil objectives at the same time. User needs analyses have shown that such missions ask for a correct mix of optical and SAR sensor observations. The sensors should be based on multi-satellite EO system combined with a fast data reception and delivery capability.

The user needs can be characterised in terms of level of service to be provided (privileges, type and number of products, etc) and required applications. Each application is related to specific acquisition requirements and constraints, as shown in fig. 1, where two main design parameters are indicated: revisit time and spatial resolution with respect to the possible application areas of EO remote sensing products. As function of the application to be covered, one may have a fairly wide range for these parameters. The most demand for revisit time and high and very high spatial resolution is related to ***Risk Management*** and ***Defence***. In the case of ***Coastal applications*** high revisit time are requested too, but the spatial resolutions are generally in the order of tens of meters. For ***Marine observation*** (i.e. open ocean and sea ice) the temporal resolution remains very high but the spatial resolution is coarser. Hinterland application such as ***Agriculture and Forestry*** generally require revisit time around 1 week. All other application (e.g. geology) require less frequent revisit time (up to seasonal) but the spatial resolution is quite variable.

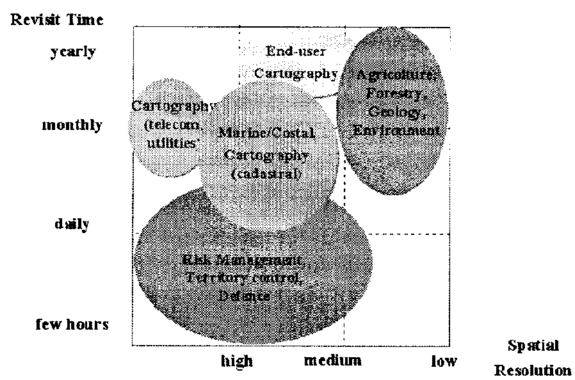

Fig. 1 - EO data applications vs. Revisit Time and Spatial Resolution

In addition to the revisit time and the spatial resolution requirements, there are other constraints on the imaging condition to be considered such as: image size, local time, incidence angle, access area, etc. All these design parameters have to be considered in the constellation design, in fact, for each specific application/product to

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be satisfied, there are very different constraints (e.g. some products may require quasi-nadir observation, while for other products it is preferred to have high incidence angles). In order to cope with these different acquisition constraints, an optimisation process has to be performed based on some design criteria as indicated in the following sections.

System drivers identification:

The system drivers identify the main mission parameters or characteristics which can influence the optimisation of performance achievements vs. cost, risk and schedule for both space and ground segment.

In a Earth Observation satellite constellation the system performance which directly or indirectly impact on the orbit design process can be summarised in a limited number of peculiar figures of merit. These figures are:

- Accessible area
- Response time
- Revisit time
- On-ground resolution
- Swath

These figures of merit can be correlated to the system parameters as indicated in the following table.

Key Parameters	Involved Parameters
Accessible area	- Number of satellites - Payload field of regards - Altitude - Orbit
Response time	- Number of satellites - Altitude - Access region - Communications - Ground station locations - Re-scheduling / Processing time
Revisit time	- Number of satellites - Altitude - Access region
On-ground resolution	- Wavelength/Aperture (Optical) - Antenna length/Bandwidth (SAR) - Altitude - Off-nadir pointing angle
Swath	- Telescope FOV - Focal Plane array size - Data rate - Satellite agility (Optical) - Antenna area - Data rate (SAR)

Tab. 1 - Key design parameters

The main parameter to be considered as cost driver is the number of operating satellite to be deployed. Therefore this important parameter shall be quantitatively related to the system performance in order to allow a clear understanding of the achievable performance w.r.t. the number of operating satellite.

Orbit and constellation design criteria:

The orbit and constellation design processes for the optical satellites and for the SAR satellites can be independently optimised. This assumption is justified by the different characteristics, acquisition constraints and operative modes of the corresponding payloads.

Few design criteria are in general applicable and therefore they are here below discussed.

Candidate Specialised Orbit

All orbits that have been considered are low Earth orbits, having an altitude ranging from 500 km up to 700 km. This restriction to the orbit altitude values is imposed by the specific optical and SAR payloads limitations (upper bound) and the drag decay effects (lower bound):

- for an optical payload this upper limitation is due to the difficulty to maintain both high resolution and limited instrument dimensions with the increasing of the altitude (for a fixed optical aperture the ground spatial resolution linearly decreases with the altitude)
- for a SAR payload this upper limitation is due to the difficulty to maintain both high SNR and limited power demand with the increasing of the altitude (for a fixed transmitted power the SNR decreases with the cube of the altitude)
- the exclusion of too low orbit altitudes is due to the drag effects that may limit the spacecraft lifetime and/or impose severe constraints on the propulsion.

Starting from this assumption the following types of orbits can be investigated:

- Elliptical orbits
- Inclined orbits
- Circular Sun-Synchronous orbits

The use of optical and SAR satellites in elliptical orbits has been investigated specially due to coverage advantages in a specific terrestrial hemisphere. In fact, when the orbit is elliptical, the satellite stays for a greater period at the apogee crossing, so allowing a major coverage in the corresponding hemisphere.

Because of the altitude range restrictions already discussed the maximum apogee altitude that can be considered is 700 km and the minimum perigee altitude that can be considered is 400 km.

So the bigger elliptical orbit that can be considered has an eccentricity equal to 0.022. This orbit presents very small eccentricity, and consequently, presents also very few advantages in terms of coverage of a specific terrestrial hemisphere, while, on the other hand, presents all environmental perturbations problems joint to the elliptical orbits.

Therefore the use of elliptical orbits is not considered applicable for remote sensing applications, where non-uniform coverage or satellite altitude and velocity variations do not always guarantee adequate instrument performance and, on the other hand, do not provide significant advantages.

Since the use of elliptical orbits is discarded, only low Earth circular orbits will be considered.

The use of in inclined orbits has been proposed specially for optical satellites in military application but:

- they cover only a limited latitude belt around the equator
- the orbit plane rotation induced by the RAAN-rate causes a variation of the illumination conditions of the target sites during the satellite passage. This means the incapability for an optical payload to acquire a target image during the dawn-dusk orbit periods (up to two months of duration)
- for the SAR satellite these orbits increase the system complexity (thermal control, solar arrays, etc) and costs

and therefore also the use of inclined orbits is discarded for EO satellites.

The use of circular SSO is definitely assumed since they allow:

- high latitude accessibility
- uniform coverage
- limited satellite altitude and velocity variations
- uniform Sun illumination conditions

Circular Sun Synchronous Orbits

In a SSO orbit the nodal regression is equal to the apparent motion of the Sun about the Earth (i.e. RAAN rate = 0.98563°/day eastward) and the ground track pattern is completely defined by the number of orbits per day Q. By indicating with D the repeating cycle (number of days) it is possible to express Q as:

$Q = [Q] + I / D \qquad [.] \equiv$ integer part

where I is an integer number ($I < D$).

By indicating with S the fundamental interval (i.e. the angular equatorial distance between two successive satellite tracks) and with Si the sub-interval (i.e. the angular equatorial distance between trace patterns day by day) we have:

$S = 360° / Q \quad$ and $\quad Si = S / D$

The appropriate choice of I and D allows the selection of the desired observation scheme.

The choice of:

$I = 1$ or $I = D - 1$ (i.e. direct orbits or drifting orbits)

allows to achieve a good sampling in space but not in time of the pointed targets (e.g. I / D = 15 / 16)

The choice of:

$n \cdot I \pm 1 = D$ or $n \cdot (D - I) \pm 1 = D$ (i.e. skipping orbits)

allows to achieve a good sampling in time with a lower spatial resolution. In this case I / D approximates a fraction with a smaller denominator, that is:

$I / D = I / (n \cdot I \pm 1) \approx 1 / n$ or

$I / D = [(n-1) \cdot D \pm 1] / (nD) \approx (n-1) / n$

and the orbit is said to have a sub-cycle equal to n-days, that is to be a near-n orbit (e.g. I / D = 13 / 16 ≈ 4 / 5 → near 5 orbit).

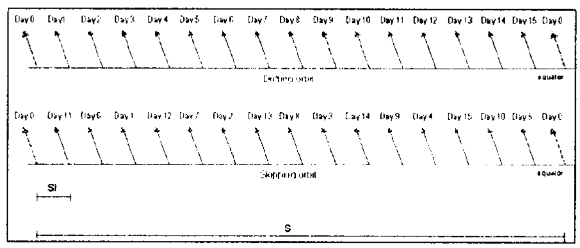

Fig. 2 - Example of ascending ground-tracks pattern at equator for a drifting orbit (e.g. 14+15/16) and for a skipping orbit (e.g. 14+13/16, near-5 orbit)

Altitude and Inclination

In a SSO the altitude and inclination are directly related (i.e. the inclination is function of the orbit altitude). For low Earth circular orbits, the sun-synchronous inclination is between 96° and 100°.

Therefore the selection of the orbit inclination shall take into account the limitations imposed by the available altitude range and the latitude belt to be covered.

For EO mission it has been assumed an altitude range of 500 ÷ 700 km, allowing the satellite ground tracks to access all sites up to +/-82° latitude.

Argument of Perigee and Eccentricity

A frozen orbit is selected for EO satellites. This type of orbit, its mean elements, specifically, argument of perigee ω and eccentricity e, have to be selected to maintain constant values with the time (or nearly constant).

The line of apsides is maintained fixed (no perigee rotation) with an argument of perigee frozen at 90 deg.

The advantage for remote sensing satellite is related to:

- a constant altitude profile over the oblate Earth from revolution to revolution, with very small altitude variation over the northern hemisphere;
- a tight longitudinal control of the ground trace (no longitudinal variations of the ground trace due to perigee rotation).

An argument of perigee of +90° results in an *de/dt* equal to zero (constant eccentricity).

A first guess of the eccentricity value can be obtained so that *dω/dt* due to first two zonal harmonics J2 and J3 is zero.

The approximated value for the eccentricity (conservative) is here below given [RD 2]:

$$e \approx -J_3 \cdot R \cdot \sin(i) / (2 \cdot J_2 \cdot a)$$

where:

$J_2 = 1.08263 \cdot 10^{-3}$

$J_3 = -2.536414 \cdot 10^{-6}$

$R = 6378.144\ km$, *equatorial radius of the Earth*

a = *semimajor axis*

i = *inclination*

It is clear that active manoeuvre within the operative life of the satellite to maintain a frozen orbit shall be in any case performed, for example to compensate the drag effects on the orbit altitude and other perturbations affecting the orbital inclination (e.g. out-plane perturbation due to solar-lunar effect) and the orbital eccentricity (e.g. in-plane perturbations due to solar radiation effects).

SAR Constellation in Sun-synchronous Orbits: Orbit Selection

The most important feature of SAR payloads is their independence from the sun illumination conditions: this allows injecting the satellite in orbits which are strongly unfavourable for optical satellites. Moreover, since images can be obtained during the night and in presence of heavy cloud cover, the SAR satellites can operate for a good percentage of the satellite orbit period, spacecraft bus resources permitting.

The SAR payload is required to operate in multiple modes trading-off, for example, geometric resolution with swath width, or geometric resolution with radiometric resolution. This allows matching the characteristics of the sensor to the specific task to be performed during each orbit period, and from orbit to orbit.

A possible solution in order to increase the SAR constellation performance, in terms of coverage and revisit time performance limiting at the same time the number of satellites and the spacecraft bus resources, is to implement a double image side capability (left-hand/right-hand) by manoeuvring the whole satellite. This means that access area is also doubled. The time required for this manoeuvre is an effective outage time and the manoeuvre cannot be performed when over-passing an area where multiple images must be taken. Therefore, all manoeuvres must be planned in advance and the spacecraft must enter the operational time slot already with a pre-set attitude.

According to the criteria addressed in previous sections the specific analysis concerning the SAR satellite orbit and constellation design is based on the following initial assumptions:

- use of circular Sun-Synchronous Orbits
- altitude ranging between 500 ÷ 700 km
- single dawn-dusk orbit plane for all the satellites

The next steps consist in the selection of a specific satellite orbit and then in the optimisation of the number of SAR satellites and their phasing on the orbit plane assuming as "key design driver" the capability of the system to guarantee adequate performance w.r.t. the number of operating satellites.

This design driver implies, in addition to a single orbit plane constellation choice, that some others orbit selection criteria should be applied:

- The global accessibility shall be achieved with only one operating satellite. For a SAR instrument this condition is surely achieved if the instrument access area at the equator is greater then the orbit basic sub-interval, that is:

  Access Area > Basic Sub-Interval Si

  Next figure depicts this concept:

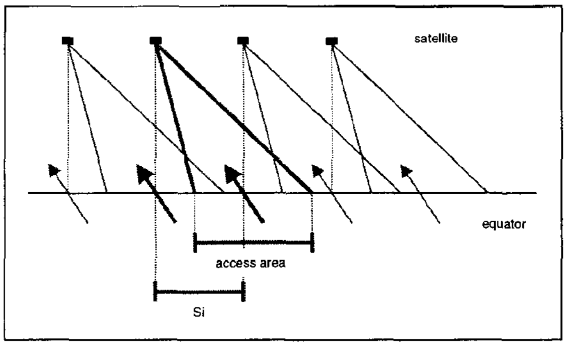

Fig. 3 - SAR instrument access area and basic sub-interval geometry

It should be pointed out that this is a very restrictive approach since in this way only the ascending or the descending orbits have been considered for the accessibility analysis. In fact, if this criteria is satisfied (i.e. Access Area > Basic Sub-Interval), all the points over the Earth's surface will be accessed either by an ascending orbit and a descending orbit during the orbit cycle. In other words this criteria guarantees the global accessibility for two times during the whole orbit cycle.

- High repeat cycle length permits to implement incidence angle diversity. In fact higher is the repeat cycle length (D) and lower is the extension of the basic sub-interval (Si), allowing the SAR instrument to acquire the same target more times during the orbit cycle and with different incidence angles. The following figure depicts this concept:

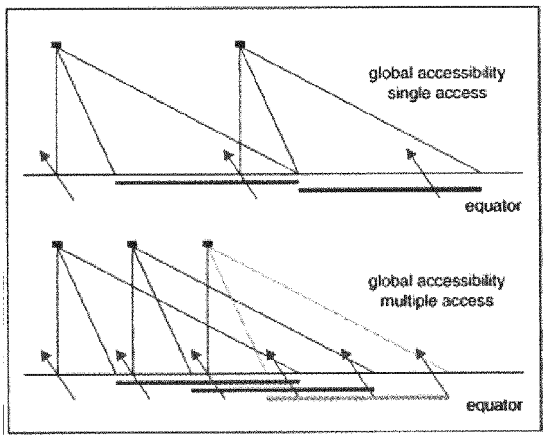

Fig. 4 - SAR instrument incidence angle diversity concept

Once that the global coverage criterion is satisfied with one satellite, the maximum revisit time is no greater then the repeat cycle interval. Within the set of orbits satisfying the global coverage criterion this would suggest to choice the orbit with the shorter repeat cycle.

On the other hand the selection of an orbit with a repeat cycle interval which exactly fits the required revisit period is usually not preferred since, in such way, a certain site would be always viewed at the same incidence angle, in contrast with the consideration of the second criterion.

Therefore, the preferred orbit shall be a skipping orbit having a near repeat cycle sufficiently small in order to provide an acceptable revisit time also in the case of availability of one operational satellites, and an effective repeat cycle sufficiently high in order to implement multiple incidence angle imagery.

Optical Constellation in SSO: Orbit Selection

The spectral observation regions covered by the optical payloads (VIS, IR and UV/Vis regions) imply some inherent limitations for the images acquisition. In particular, they can only sense the sunlight part of the Earth (except for IR bounds), this means that more than one half of each orbit is useless for images acquisition.

Moreover, the image acquisition for the polar regions during solstices is critical due to the poor illumination condition of the scene.

In particular at winter solstice all latitudes above 67° north cannot be accessed by the optical instrument, and assuming 15° degrees the minimum sun incidence angle allowing a reliable image acquisition only targets below 52° north can be effectively acquired.

As a result, an optical satellite can only take images during, theoretically, less than 40 % of the orbit period in average.

The necessity to optimise the illumination condition of the Earth scene drives the selection for optical satellites of near-noon sun-synchronous orbits. In fact, these orbits provide sufficient and near constant sun illumination of the Earth surface (for the orbit portion that is out of eclipse).

The cloud cover represents also a possible limitation for optical images acquisition, The cloud cover is known to be in the order of 30% to 70% of the time at all latitudes, except for very arid climatic zones. This effect further reduces the useful portion of the orbit period for optical satellites.

According to the criteria addressed in previous sections the specific analysis concerning the optical satellite orbit and constellation design is based on the following initial assumptions:

- use of circular Sun-synchronous orbits
- altitude ranging between 500 ÷ 700 km
- single near-noon orbit plane for all the satellites

In particular the local time will be chosen between 10:00÷11:00 am for image acquisition performed during the descending orbits, or between 01:00÷02:00 pm for image acquisition performed during the ascending orbits, in order to image areas at high latitudes with the highest sun incidence (i.e. near noon).

The next steps consist in the selection of a specific satellite orbit and then in the selection of the number of optical satellites and their phasing on the orbit plane assuming as "key design driver" the capability of the system to guarantee adequate performance w.r.t. the number of operating satellites.

As already seen for the SAR constellation this design driver implies, in addition to a single orbit plane constellation choice, that some others orbit selection criteria should be applied:

- the global accessibility shall be achieved with only one operating satellite. For an optical instrument this condition is surely achieved if the instrument' access area at the equator is greater then the orbit basic sub-interval, that is:

Access Area > Basic Sub-Interval Si

Next figure depicts this concept:

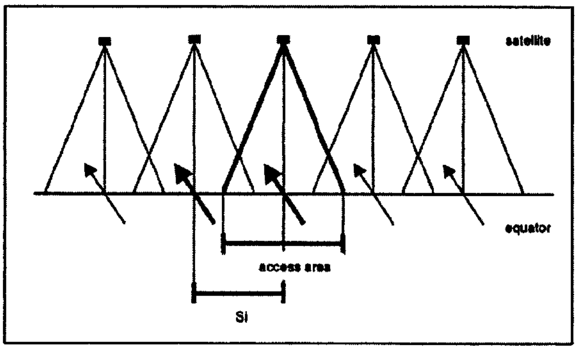

Fig. 5 - Optical instrument access area and basic sub-interval geometry

- All the accessible sites should be potentially observed during the repeat cycle at least once time with a quasi-nadir observation geometry (i.e. low off-nadir looking angles) in order to reach the maximum performance (maximum spatial resolution, minimum image degradation due to the off-nadir observation). Moreover, high repeat cycle length permits to implement incidence angle diversity. In fact higher is the repeat cycle length (D) and lower is the extension of the basic sub-interval (Si), allowing the optical instrument to acquire the same target more times during the orbit cycle and with different incidence angles. This is particular important in observing targets casting shadows depending from the sun vector angle. Incidence angle diversity can also be exploited by multispectral acquisition, for classification tasks: in fact the response of vegetation in the various bands does also depends from the sun vector incidence. The following figure depicts this concept:

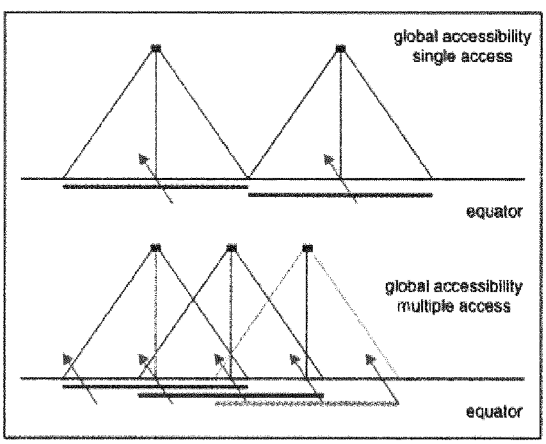

Fig. 6 - Optical instrument incidence angle diversity concept

Once that the global coverage criterion is satisfied with one satellite, the maximum revisit time is no greater then the repeat cycle interval. Within the set of orbits satisfying the global coverage criterion this would suggest to choice the orbit with the shorter repeat cycle.

On the other hand the selection of an orbit with a repeat cycle interval which exactly fits the required revisit period is usually not preferred since, in such way, a certain site would be always viewed at the same incidence angle (up to 35° off-nadir, with a high image degradation), in contrast with the consideration of the second criterion.

Therefore, the preferred orbit shall be a skipping orbit having a near repeat cycle sufficiently small in order to provide an acceptable revisit time also in the case of availability of one operational satellites, and an effective repeat cycle sufficiently high in order to provide a quasi-nadir observation capability of the accessible sites within the orbit cycle.

The selection of a candidate orbit with the sub-cycle equal to the required revisit period and with a longer repeat cycle entails that the global accessibility shall be achieved by one operating satellite within the sub-cycle. This means that the following stronger condition must be verified:

Access Area > Sub-Cycle Basic Sub-Interval

<u>*Number of Satellites*</u>

The number of satellites is a driver factor for the overall system cost. Therefore the selection of the number of satellites shall be minimised considering the result of a trade-off between the achievable figures of merit (in terms of coverage and revisit time) and the system cost and complexity.

<u>*Number of Orbit Planes for each Constellation and Satellite Phasing*</u>

The number of orbit planes is one of the principal characteristics of any satellite constellation. It is important to guarantee adequate performance w.r.t. the number of operating satellites, this means that one would like to achieve some performance level as soon as the first satellite is operative and to raise that level of performance with each succeeding satellite.

In terms of constellation growth and degradation a single-plane constellation has some advantages w.r.t. constellations with multiple orbit planes:

- a new performance plateau is reached for each added satellite
- if a satellite fails, we may re-phase the remaining satellites with limited propellant consumption (in-plane manoeuvring) leading to a graceful degradation of the system. Re-phasing a satellite in a multiple plane constellation may be prohibitive (high propellant consumption for out-of-plane

manoeuvring and/or excessive time for manoeuvring completion).

In terms of optical and SAR payloads mission a single-plane constellation has some advantages w.r.t. constellations with multiple orbit planes:

- using a single near-noon orbit plane the optical payloads will acquire the images with the better and the same illumination conditions
- using a single dawn-dusk orbit plane for the SAR satellites allows the maximisation of the orbit period out of the eclipse, satisfying the spacecraft high power needs and, as a second instance, allowing a simplification of system complexity in terms of thermal control and solar arrays (sizing and Sun pointing)

The phasing of the satellites on the orbit plane is selected in order to achieve the optimisation of the performance in terms of coverage and revisit time.

The following table resumes the design variables that shall be addressed during the EO constellation design:

Design Variables	Major Effects	Selection Criteria
Altitude	- Coverage - Revisit time	System level trade-off (payload complexity, lifetime, etc.)
Inclination	- Latitude distribution of coverage	SSO: related to altitude
Number of Satellites	- System Cost - Coverage - Revisit time	Minimum number w.r.t. required figures of merit
Number of Orbit Planes	- Performance plateaus - Constellation growth and degradation	Constellation building/launch strategy
Satellite Phasing	- Coverage - Revisit Time	Performance optimisation

Tab. 2 - Selection criteria

A case study:

It is now possible to apply these general criteria to a specific case study. In particular for the system drivers deriving from the optical and the SAR payload characteristics we have considered as a reference the experience already made within the COSMO-SkyMed space program [RD 3] for the SAR and Optical constellation design.

According to these system drivers it is assumed that the SAR payload measurement geometry allows an off-nadir access between 22.7° ÷ 44.3° (only right looking) and that the Optical payload has a Field Of View wrt. nadir of ±35°. Next figures show the corresponding observation geometry.

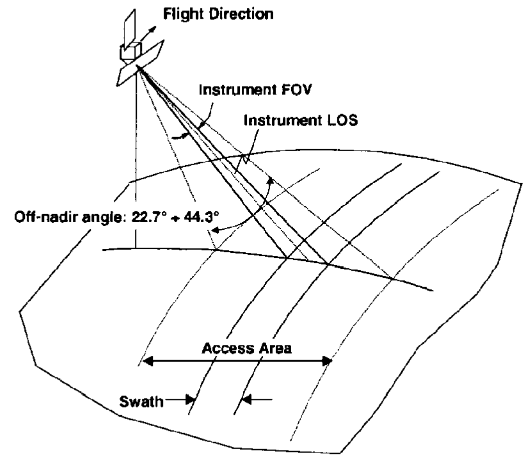

Fig. 7 - SAR payload observation geometry

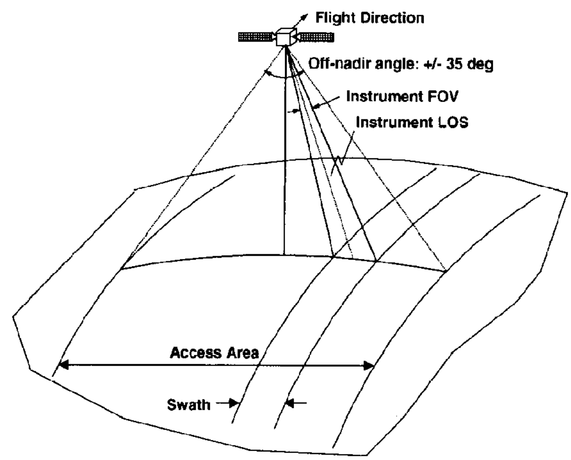

Fig. 8 - Optical payload observation geometry

SAR Constellation

In the following table the basic sub-interval and the satellite access area extensions are shown for SSO having an increasing repeat cycle (i.e. D = 2,3,...,10) and an altitude between the imposed range (i.e. 500 ÷ 700 km) and assuming an off-nadir angle ranging between 22.7°÷ 44.3°.

I	N	D	Q	H (km)	Si (km)	Access Area (km)
14	1	2	14,50	720	1381	446
14	2	3	14,67	666	910	409
14	3	4	14,75	639	679	392
14	4	5	14,80	624	541	381
14	5	6	14,83	613	450	374
14	6	7	14,86	606	385	369
14	7	8	14,87	600	336	366
14	8	9	14,89	596	299	363
14	9	10	14,90	592	268	360

Tab. 3 - SAR instrument access area and basic sub-interval extensions

The table shows that this condition automatically excludes the orbits with repeat cycles less than 8 days, in fact, orbits with repeat cycle less than 8 days have a resultant access area smaller than the basic sub-interval.

As already observed this is a very restrictive approach since it consider only the ascending or the descending orbits have for the accessibility analysis. Access simulations have shown that orbits having a near repeat cycle ≥ 5 provide an acceptable revisit time also in the case of availability of only one operational satellites (i.e. about 90% target accessibility within the cycle).

According to the design criteria addressed the final selection is performed by identifying the SSO that:

- has a repeat cycle ≥ 8 days (i.e. global accessibility)
- has an access area at least two times greater than the basic sub-interval in order to guarantee global accessibility to the Earth's surface with at least two different incidence angles (i.e. incidence angle diversity)
- has a near repeat cycle equal to 5 days (i.e. revisit time optimisation with one satellite)

According to the above mentioned rational design criteria the following candidate orbit has been selected:

Q = 14.8125 orbits per day SSO

(i.e. 14+13/16, h=619.6Km, i =97.86°, e = 0.00118, AOP=90°)

In fact it guarantees an operational altitude in the range of 500-800 Km, global accessibility with one satellite, incidence angle diversity and the lowest near repeating cycle. The values selected for the eccentricity and the argument of perigee guarantee a frozen orbit solution.

The selection of the number of satellites is minimised by performing a trade-off between the achievable figures of merit and the system cost. For the selected orbit simulation analyses are performed in order to find the average and the maximum revisit times for different latitudes. These performances have been computed by taking into account one, two, three or four operational satellites being elements of the final SAR constellation placed on the same orbital plane and with the following phasing among the satellites:

Number of Satellites	True Anomaly
1	0°
2	0°, 180°
3	0°, 120°, 240°
4	0°, 90°, 180°, 270°

Tab. 4 - SAR satellites phasing

Next figures provide the results:

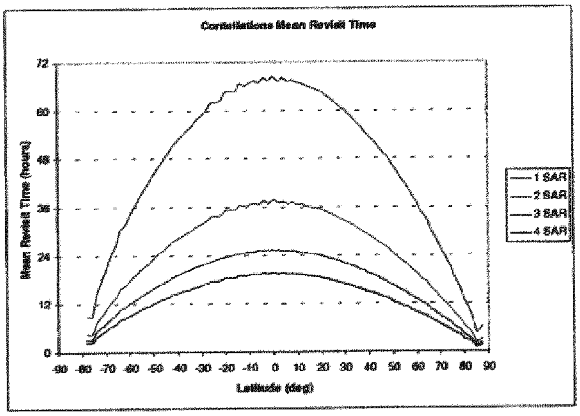

Fig. 9 - SAR constellation mean revisit time vs. satellite number

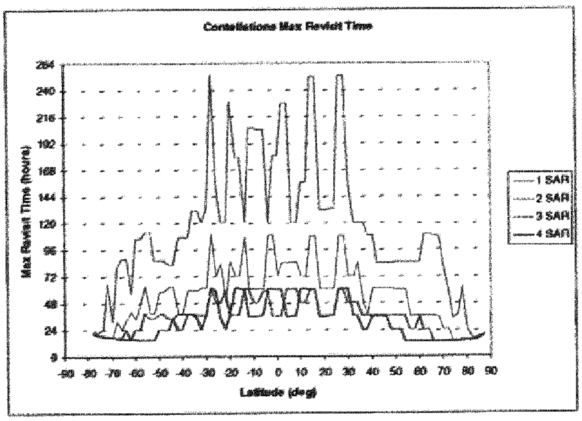

Fig. 10 - SAR constellation maximum revisit time vs. satellite number

The following table summarises the achievable performance in the latitude range 20°÷60° wrt the number of operating satellites.

1 satellite	37 ÷ 64 h	mean
	< 252 h	max
	- 38% (24h)	access
2 satellites	19 ÷ 35 h	mean
	< 108 h	max
	41% (12h) 64% (24h)	access
3 satellites	13 ÷ 24 h	mean
	< 60 h	max
	62% (12h) 84% (24h)	access
4 satellites	10 ÷ 18 h	mean
	< 60 h	max
	80% (12h) 95% (24h)	access

Tab. 5 - SAR constellation @ 619.6 km: summary of performance results

Optical Constellation

In the following table the basic sub-interval, the satellite access area extensions and the squint degradation factor (i.e. ratio of the achievable spatial resolution at nadir and the resolution at the FOV angle limit, that is at half basic sub-interval) are shown for SSO having an increasing repeat cycle (i.e. D = 2,3,...,10) and an altitude between the imposed range (i.e. 500 ÷ 700 km) and assuming an instrument FOV of ±35°.

I	N	D	Q	h (km)	Si (km)	Access Area (km)	Squint degrad.
14	2	3	14,67	666	910	959	54,0
14	3	4	14,75	639	679	919	31,6
14	4	5	14,80	624	541	897	20,8
14	5	6	14,83	613	450	880	14,8
14	6	7	14,86	606	385	870	11,0
14	7	8	14,87	600	336	861	8,6
14	8	9	14,89	596	299	855	6,8
14	9	10	14,90	592	268	849	5,6
14	10	11	14,91	589	244	854	4,6
14	11	12	14,92	587	224	851	3,9
14	12	13	14,92	585	207	848	3,4
14	13	14	14,93	583	192	845	2,9
14	14	15	14,93	582	179	843	2,5
14	15	16	14,94	580	168	841	2,2

Tab. 6 - Optical instrument access area and basic sub-interval extensions

The table shows that this condition automatically excludes the orbits with repeat cycles less than 3 days, in fact, orbits with repeat cycle less than 3 days have a resultant access area smaller than the basic sub-interval.

A squint degradation factor next to one means a quasi constant performance over the entire accessible area.

Therefore the selection can be performed by identifying the orbits that:

- have a repeat cycle ≥ 3 days (i.e. global accessibility)
- have a squint degradation factor lower then 2% (i.e. a quasi-nadir observation capability)
- have a near repeat cycle equal to 3÷5 days (i.e. revisit time optimisation with one satellite)

Therefore, as a result of this trade-off these two candidate orbits has been deeply analysed:

- the Q = 14.8125 orbits per day SSO (i.e. 14 + 13 / 16, h=619.6 km)
- the Q = 14.6875 orbits per day SSO (i.e. 14 + 11 / 16, h=659.3 km)

They both guarantee an operational altitude in the range of 500-700 Km, low off-nadir degradation factor (lower then 2%), incidence angle diversity and a near repeating cycle of 5 and 3 days respectively for a global accessibility. This means that also when only one satellite is operational the maximum waiting time for each point on the Earth surface is 5 and 3 days respectively. Therefore the second orbit guarantees a better revisit time but with an higher altitude degradation factor.

The selection of the number of satellites is minimised by performing a trade-off between the achievable figures of merit (in terms of coverage and revisit time) and the system cost.

For the selected orbits the fundamental interval S is 2705 km and 2728 km at equator and the access area is 899 km and 957 km respectively. As a consequence three satellites equi-phased on a single orbit plane are sufficient to provide a revisit time less than 1 day in both cases, that is a maximum revisit time of about 24 hours for the visible channels (and less than 12 hours for IR channels). This is the minimum value achievable for an optical payload with a SSO. Therefore the optimum satellite number to be analysed is in the range of 1 ÷ 3.

For each of the selected orbits simulation analyses have been performed in order to find the average and the maximum revisit times for different latitudes, and for different optical constellation configurations and sensor operation modes. These performances have been computed by taking into account one, two or three operational satellites being elements of the final optical constellation placed on the same orbital plane and with the following phasing among the satellites:

Number of Satellites	True Anomaly
1	0°
2	0°, 180°
3	0°, 120°, 240°

Tab. 7 - Optical Satellites Phasing

Next figures provide the results:

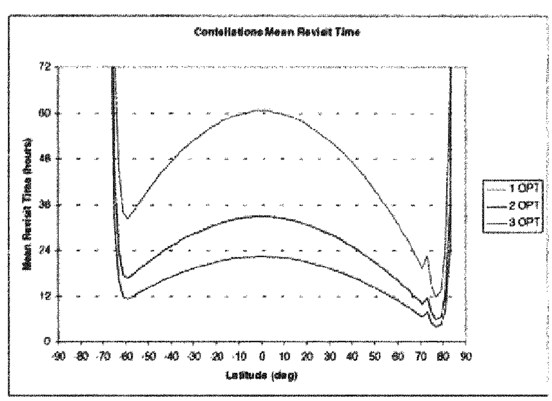

Fig.11 - Optical constellation @ 619.6 mean revisit time vs. satellite number

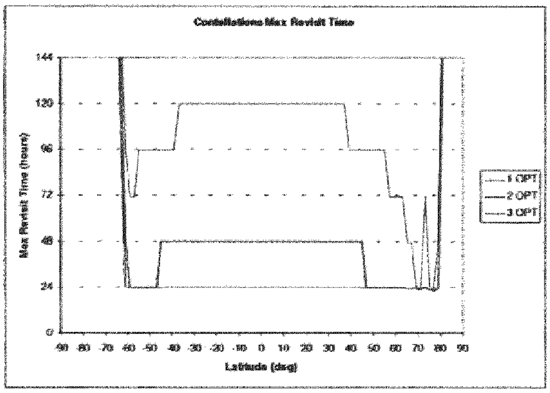

Fig. 12 - Optical constellation @ 619.6 maximum revisit time vs. satellite number

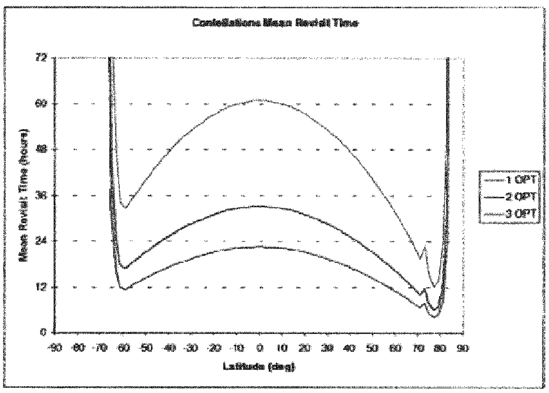

Fig. 13 - Optical constellation @ 619.6 mean revisit time vs. satellite number (nominal mode)

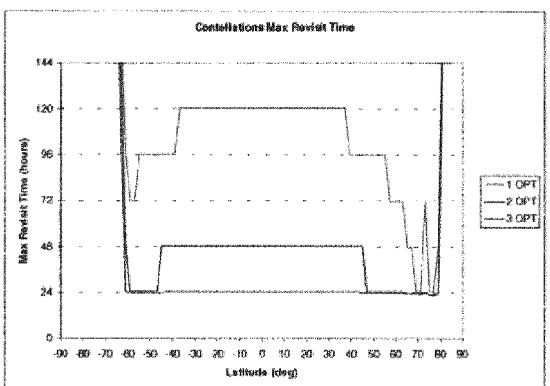

Fig. 14 - Optical constellation @ 619.6 maximum revisit time vs. satellite number (nominal mode)

The following tables summarise the achievable performance in the latitude range of 20°÷60° wrt the number of satellites for both selected orbits.

1 satellite	32 ÷ 53 h	mean
	< 120 h	max
	48% (24h)	access
2 satellite	17 ÷ 31 h	mean
	< 48 h	max
	89% (24h)	access
3 satellite	11 ÷ 21 h	mean
	< 24 h	max
	100% (24h)	access

Tab.8 - Optical constellation @ 619.6 km: summary of performance results

1 satellite	30 ÷ 54 h	mean
	< 72 h	max
	51% (24h)	access
2 satellite	16 ÷ 29 h	mean
	< 48 h	max
	92% (24h)	access
3 satellite	11 ÷ 20 h	mean
	< 24 h	max
	100% (24h)	access

Tab. 9 - Optical constellation @ 659.3 km: summary of performance results

Conclusions:

The design concepts described in this paper have been already applied in space projects where satellite constellations features have been exploited.

The optimisation process as here outlined can be easily adapted for other mission studies simply modifying the corresponding driving criteria and the payload characteristics.

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